Stratification of Soil Organic Matter and Potential Impact on Water Runoff Quality

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Abstract

Soil quality is a concept based on the premise that management can deteriorate, stabilize, or improve soil ecosystem functions. Soil organic matter is a key component of soil quality that sustains many key soil functions by providing the energy, substrates, and biological diversity to support biological activity, which affects (1) aggregation (important for habitat space, oxygen supply, and preventing soil erosion), infiltration (important for leaching, runoff, and crop water uptake), and decomposition (important for nutrient cycling and detoxification of amendments). Lack of residue cover and exposure of soil to high-intensity rainfall can result in poor aggregation, reduced plant water availability, erosion, and off-site impacts of sedimentation and poor water quality. It is hypothesized that the degree of soil organic matter stratification could indicate soil quality or soil ecosystem functioning. A review of literature was conducted to relate soil organic matter stratification to water runoff quality. Despite high concentrations of surface soil nutrients associated with high soil organic matter stratification, water runoff volume and quality do not appear to be at much greater risk of loss, except for an increase in bioavailable P. Further research is needed to quantify relationships.

Keywords: Animal manure; Conservation tillage; Fertilization; Nitrogen; Organic carbon; Water quality

1. Introduction

Soil provides a medium for plant growth, regulates and partitions water flow in the environment, and buffers the fluxes of natural and xenobiotic compounds through decomposition and fixation processes (Doran et al., 1994). The organic components of soil are important in providing energy, substrates, and the biological diversity necessary to sustain many soil functions.

Conservation tillage systems are now widely adopted by many producers, because they

- reduce fuel, time, and labor needed to make multiple tillage operations,
- reduce machinery wear
- allow for more timely planting of crops even under wetter soil conditions
- improve soil and water quality
- reduce runoff and make more effective use of precipitation
- improve wildlife habitat
- meet Farm Bill requirements

Stratification of soil organic matter with soil depth is common in many natural ecosystems and managed grasslands and forests (Schnabel et al., 2001), as well as cropland under long-term conservation tillage (Stockfisch et al., 1999). The soil surface is the vital interface that (1) receives much of the fertilizers and pesticides applied to cropland, (2) receives the intense impact of rainfall, and (3) partitions the flux of gases into and out of soil. It has been hypothesized that the degree of stratification can be used as an indicator of soil quality or soil ecosystem functioning, because surface organic matter is essential to erosion control, water infiltration, and conservation of nutrients (Franzluebbers, 2002). The objective of this report is to review available literature on how adoption of conservation tillage that leads to stratification of soil organic matter might affect water runoff volume and quality. There is growing concern that continual manure application to pasture or conservation-tilled soils might lead to deterioration of surface water quality from the accumulation of P at the soil surface (Sharpley, 2003). A review of literature is needed to determine the potential interactions between stratification of soil organic matter and water quality.

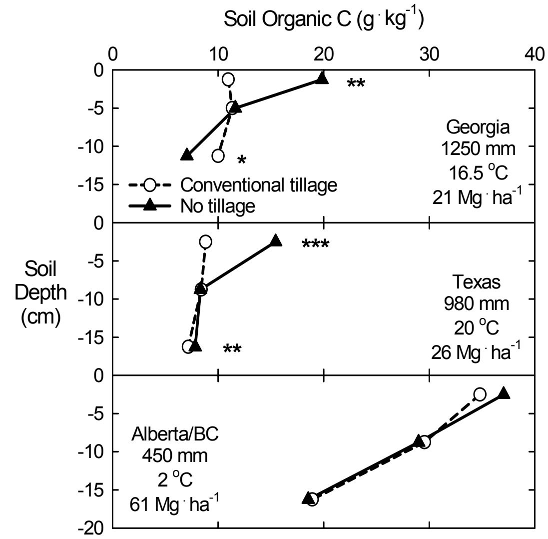

Figure 1. Depth distribution of soil organic C under long-term, conventional- and no-tillage management in three different regions of North America. From Franzluebbers (2002).

2. Review of studies

2.1. Conservation tillage and stratification of soil organic matter fractions

Soil organic C under long-term conservation tillage systems is often more stratified with depth than under conventional, inversion tillage (CT) (Fig. 1). This difference develops as a result of crop residues left at the soil surface, where temperature and moisture fluctuations limit decomposition and result in accumulation of soil organic C.

Many soil organic matter fractions can become stratified with depth, including total, particulate organic, microbial biomass, and mineralizable C and N (Franzluebbers, 2002). The degree of stratification appears to depend upon the soil organic matter fraction, soil type, climatic conditions, management, and time (Fig. 2). Stratification of total soil N at the end of 20 years of conservation-tillage management on

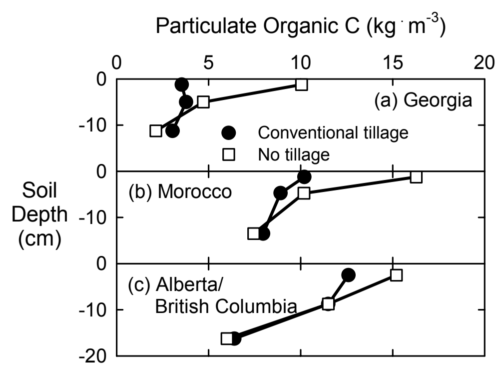

Figure 2. Depth distribution of particulate organic C under conventional and no tillage from (a) a Typic Kanhapludult at the end of 4 years in Georgia (Franzluebbers et al., 1999), (b) a Vertic Calcixeroll at the end of 11 years in Morocco (Mrabet et al., 2001), and (c) the mean of four Cryoboralfs at the end of 4 to 16 years in Alberta/British Columbia (Franzluebbers and Arshad (1997).

a silt loam in Kentucky increased with increasing N fertilization (Fig. 3). Accumulation of total N at the soil surface was likely a function of greater crop production that contributed to surface residue accumulation and subsequent decomposition at the soil surface (Ismail et al., 1994).

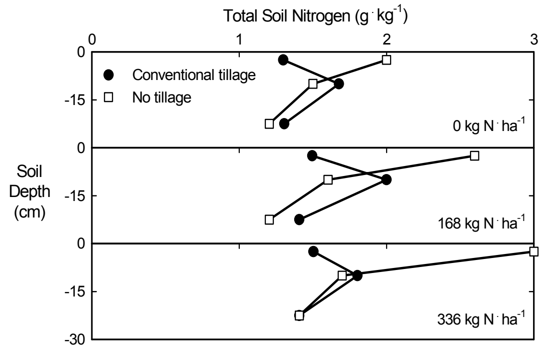

Figure 3. Depth distribution of total soil N as affected by tillage and fertilization on a silt loam in Kentucky. Data from Ismail et al. (1994).

2.2. Conservation tillage and stratification of soil P

With the continuous application of P fertilizer (either inorganic or organic), stratification of soil P can occur in the soil profile, especially under conservation tillage. Different research organizations determine soil P with different extraction protocols, because of variations in management goals, soil mineralogy, and historical calibrations for various crops. Despite these differences, greater stratification of soil P under conservation tillage than under CT was observed at the end of 9 years on a silty clay loam in Texas (Fig. 4a), at the end of 5 years in a wheat/soybean double cropping system on a sandy loam in Georgia (Fig. 4b), and at the end of 11 years on three silt loam soils in Maryland (Fig. 4c). At present, the accumulation of total and labile soil P at the soil surface under conservation tillage is viewed as a threat to water quality from water runoff (Sharpley, 2003).

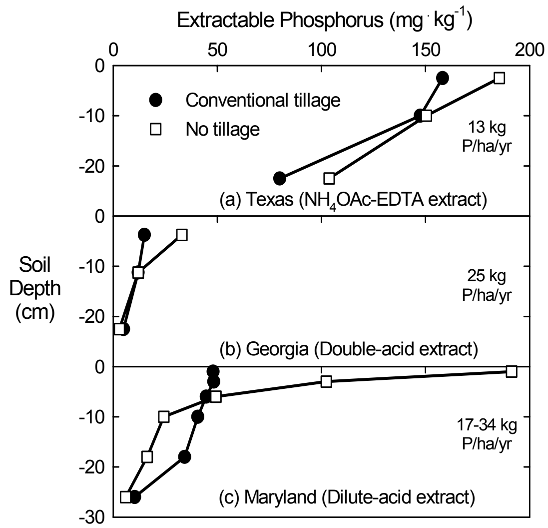

Figure 4. Depth distribution of extractable soil P under conventional and no tillage from (a) Texas (Franzluebbers and Hons, 1996), (b) Georgia (Hargrove et al., 1982), and (c) Maryland (Weil et al., 1988).

2.3. Conservation tillage and water runoff quality

Water runoff quality as affected by tillage has been evaluated using a variety of techniques, from short-term, small-plot rainfall simulations (<10 m^2) to field plots over seasons (<0.1 ha) to water catchments integrated across landscape positions and time and years (>1 ha). Each technique has their advantages and disadvantages, which can help to interpret the effect of management on water runoff quality.

On a Typic Argiudoll in Wisconsin, mean soil P losses during 1-hr rainfall simulation events in summer and autumn were lower under no tillage (NT) than under CT (Table 1). Loss of P in runoff was statistically lower under NT than under CT in (a) 6 of 6 events for total P, (b) 2 of 6 events for dissolved P, and (c) 5 of 6 events for bioavailable P (Andraski et al., 1985). Despite extractable soil P was greater under NT than under CT, especially near the soil surface, runoff loss of P fractions was mitigated by the presence of surface residue and high surface soil organic C.

Table 1. Mean loss of P in runoff from 1.35 m^2 plots during six rainfall simulation events (73 to 136 mm h^{-1}) on a silt loam under conventional tillage (moldboard plow) and no tillage in a maize cropping system in Wisconsin. Data from Andraski et al. (1985).

Tillage system	Soil organic C[a]	Extractable soil P[a]	Phosphorus loss		
			Total	Dissolved	Bioavailable
	Mg ha^{-1}	mg kg^{-1}	------------ kg ha^{-1} $event^{-1}$ ------------		
Conventional	32.5	39	1.31	0.02	0.21
No tillage	38.3	62	0.18	0.01	0.03

[a] Soil properties at a depth of 0 to 2.5 cm.

On an Ultic Hapludalf in Virginia, mean runoff volume and losses of soil sediment, N, and P following maize harvest were lower under NT than under CT (Table 2). Management at the site was under wheat (tilled) / soybean (NT) double-crop rotated with maize (NT) for a number of years. Although soil organic matter was not determined, it was expected to be stratified with depth based on management history. By inverting soil with plow tillage, nutrient concentrations in runoff were greater compared with undisturbed soil (Ross et al., 2001). Dissolved N (NO_3 + NH_4) in runoff from NT was approximately half of contents in runoff from CT. However, dissolved P (PO_4) in runoff from NT was 4 times greater than from CT. Phosphorus loss with CT was 95% associated with sediment, while that with NT was 77% associated with the dissolved fraction.

Table 2. Mean runoff volume and loss of sediment, N, and P in runoff from 112 m^2 plots during three consecutive rainfall simulation events (1, 0.5, and 0.5 h events at 43 mm h^{-1}) on a loam under conventional tillage (moldboard plow) and no tillage with various nutrient amendments following maize harvest in Virginia. Data from Ross et al. (2001).

Tillage / fertilizer	Runoff	Sediment	N	P
	mm	----------- kg ha^{-1} -----------		
Conventional + inorganic	46	3558	10.3	4.1
No tillage + inorganic	10	18	0.5	0.3
No tillage + poultry litter	11	34	0.6	0.4
No tillage/subsoil + inorganic	11	5	0.5	0.3
No tillage without fertilizer	14	21	0.6	0.3

On a Typic Kanhapludult in Georgia, mean runoff concentration of NO_3-N across several naturally occurring runoff events throughout several years was relatively similar across tillage systems (Table 3). Runoff

Table 3. Mean runoff characteristics of N and P from 270 m^2 plots during two evaluation periods under naturally occurring rainfall events on a sandy loam under conventional tillage (CT, disk plow) and no tillage (NT) with inorganic and poultry litter applied to cotton/rye (Year 6; Endale et al., 2001) and maize/rye (Years 9-11; Endale et al., 2004) in Georgia.

Condition	CT	NT
Runoff P concentration (mg L^{-1}) – Year 6		
Inorganic	0.2	0.7
Poultry litter	0.3	1.4
Runoff P concentration (mg L^{-1}) – Years 9-11		
Inorganic	0.6	4.0
Poultry litter	1.5	6.8
Runoff NO_3-N concentration (mg L^{-1}) – Years 9-11		
Inorganic	1.7	1.5
Poultry litter	0.9	1.0

concentration of PO4-P was greater under NT than under CT, with differences greater in the cropping system receiving poultry litter (Endale et al., 2004). Water runoff volume averaged 100 mm from CT and 56 mm from NT from April to November in Year 6 of the study (Endale et al., 2001). This study indicates that runoff loss of nitrate was lower with NT compared with CT, but that runoff loss of phosphate was greater with NT.

From paired watersheds in the Southern Plains USA, mean soil loss and P in runoff were lower under NT than under CT (Table 4). Soil organic matter was not reported in this study, but was expected to be higher under NT than under CT. These results indicate that despite water runoff volume was NT $\geq$ CT, nutrient runoff concentration was reduced with NT. However, runoff loss of bioavailable P tended to be greater with NT than with CT, suggesting that overland flow of water without sediment transport was still carrying dissolved nutrients.

Table 4. Mean runoff volume (% of rainfall), soil loss, and P from 2.8 $\pm$ 0.8-ha watersheds during 5 years under conventional tillage and no tillage at 3 locations in Oklahoma and Texas. Data from Sharpley et al. (1992).

Tillage	Runoff	Soil loss	P in runoff Particulate	Bioavailable	Total
	%	Mg ha^{-1}	------------ kg ha^{-1} yr^{-1} ------------		
Bushland TX, Torrertic Paleustoll (54 cm rainfall)					
Stubble mulch	5	0.9	0.5	0.1	0.5
No tillage	8	0.5	0.3	0.2	0.4
Woodward OK, Typic Ustochrept (60 cm rainfall)					
Disk tillage	17	39.6	14.4	0.9	14.9
No tillage	23	1.9	1.8	1.5	2.9
El Reno OK, Udertic Paleustoll (74 cm rainfall)					
Plow tillage	20	12.8	5.7	1.2	5.9
No tillage	24	0.4	0.5	1.4	1.7

In Mississippi, soil loss with inversion tillage was 18 Mg ha^{-1} yr^{-1} and with conservation tillage was 3 $\pm$ 2 Mg ha^{-1} yr^{-1} (McGregor et al., 1975). On a 2.7-ha water catchment in Georgia, soil loss with inversion tillage for 2.5 years was 23 Mg ha^{-1} yr^{-1} and with conservation tillage for 24 years was <1 Mg ha^{-1} yr^{-1} (Endale et al., 2000). In the latter study, stratification ratio of soil organic C (0-5:12.5-20 cm) was 3.3 at the end of 24 years of conservation tillage (Franzluebbers and Stuedemann, 2002) and was expected to be 1-2 under CT.

3. Summary and conclusions

Stratification of soil organic matter with conservation tillage generally reduces water runoff volume and sediment transport from agricultural fields. Total loss of nutrients is often reduced with conservation tillage, because of a reduction in sediment-borne nutrients. Bioavailable P in water runoff appears to be a threat to water quality, although quantitative relationships of how it might affect water quality need to be developed. This review showed that conservation tillage can mitigate sediment and nutrient loss to the environment. It also showed that further studies are needed to quantify soil organic matter stratification to better assess water runoff and quality.

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